Exploration of a singly-bottom tetraquark on $2+1$ flavour lattices

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w/ A. Francis, R. J. Hudspith, R. Lewis, K. Maltman

June 17 2019

Doubly-heavy tetraquarks

- ★ Phenomenology $\rightarrow$ bound doubly-heavy tetraquarks
  - In heavy Q limit, anti-diquark behaves like single heavy quark
    - Evident from small meson & baryon hyperfine splittings
  - good-light-diquark $\rightarrow J^P = 1^+$ tetraquark most favourable
    - i.e. should expect deepest binding
- ★ Recent years has seen progress in lattice QCD calculations of tetraquarks with $J^P = 1^+$
  - Static $\bar{b}\bar{b}$ potentials:
    - P. Bicudo & M. Wagner [1209.6274]
    - Z. S. Brown & K. Orginos [1210.1953]
    - P. Bicudo, J. Scheunert & M. Wagner [1612.02758]
  - NRQCD $\bar{b}\bar{b}$:
    - A. Francis, R. J. Hudspith, R. Lewis, K. Maltman [1607.05214]
    - P. Junnarkar, N. Mathur & M. Padmanath [1810.12285]
    - L. Leskovec, S. Meinel, M. Pflaumer & M. Wagner [1904.04197]
  - RHQ & NRQCD $\bar{c}\bar{b}$:
    - A. Francis, R. J. Hudspith, R. Lewis, K. Maltman [1810.10550]
  - For review: see A. Francis Plenary, Mon @ 10:30

Stable $J^P = 1^+$ tetraquarks on the lattice

A. Francis, R. J. Hudspith, R. Lewis, K. Maltman [1607.05214]
A. Francis, R. J. Hudspith, R. Lewis, K. Maltman [1810.10550]

We are participating in this through the study of various $qq'\bar{Q}\bar{Q}'$ states. The results already having appeared in the literature include:

- ★ $ud\bar{b}\bar{b}$ binding: $-189(10)(3)$ MeV
  - Multiple groups find evidence for strongly bound state
- ★ $ls\bar{b}\bar{b}$ binding: $-98(7)(3)$ MeV
- ★ $ud\bar{c}\bar{b}$ binding: $-38(23)$ MeV
  - Around region of $DB\gamma$ threshold
- ★ Study with variable heavy mass helps understand physics
  - includes variable masses with $Q' \neq Q$

The $ud\bar{s}\bar{b}$ channel

We move to $ud\bar{s}\bar{b}$, the simplest system for which:

- ★ Light-quark-antiquark configuration not present for ordinary meson or baryon, so does not provide constraints on $ud\bar{s}\bar{b}$
  - Doubtful that $\bar{s}\bar{b}$ can be viewed as a near-static color source
- ★ There is still a good light-diquark-anti-diquark configuration
- ★ There exist phenomenological models that predict binding that involve unconstrained light-quark model interactions
  - See, e.g. Huang & Ping [1902.05778] as a recent example
- ★ Therefore, $ud\bar{s}\bar{b}$ is an interesting exotic state to explore on the lattice since:
  - We can test the reliability of using models in exotic channels where interactions not fully constrained by phenomenology
  - Lattice can provide targets for improving such models
  - Its existence would be good for experimental search

Lattice setup

	E_H	E_M	E_L	
$L^3 \times T$	$32^3 \times 64$	$32^3 \times 64$	$32^3 \times 64$	$48^3 \times 64$
κ_l	0.13754	0.13770	0.13781	0.13781
am_π	0.18928(36)	0.13618(46)	0.07459(54)	0.0604(14)
m_π [MeV]	415	299	164	~ 133
# Configs	400	800	195	94

- ★ $N_f = 2 + 1$ Wilson-Clover gauge configuration by PACS-CS Collaboration
- ★ $a = 0.0907(13)$ fm, $a^{-1} = 2.194(10)$ GeV
- ★ $\kappa_s = 0.13640$
- ★ Larger volume extends ensemble
  - Used for preliminary results in this talk

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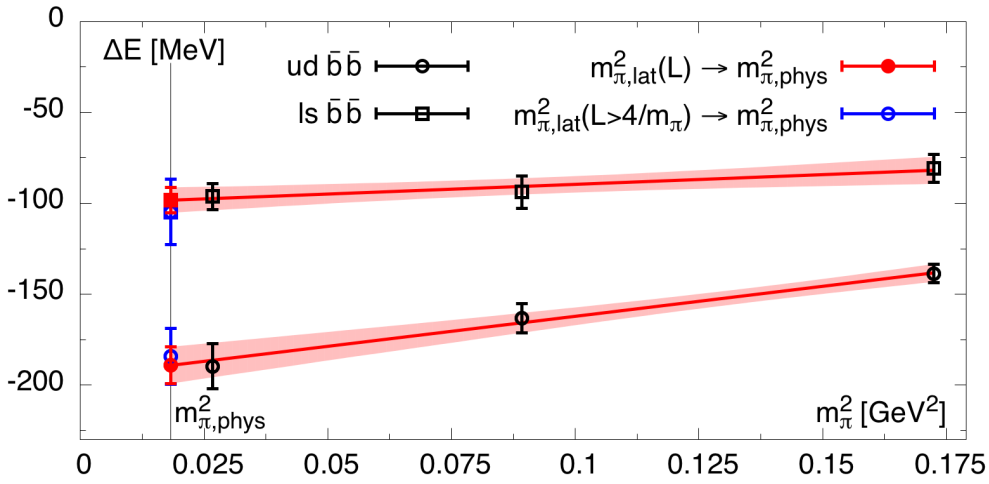
Valence Sector

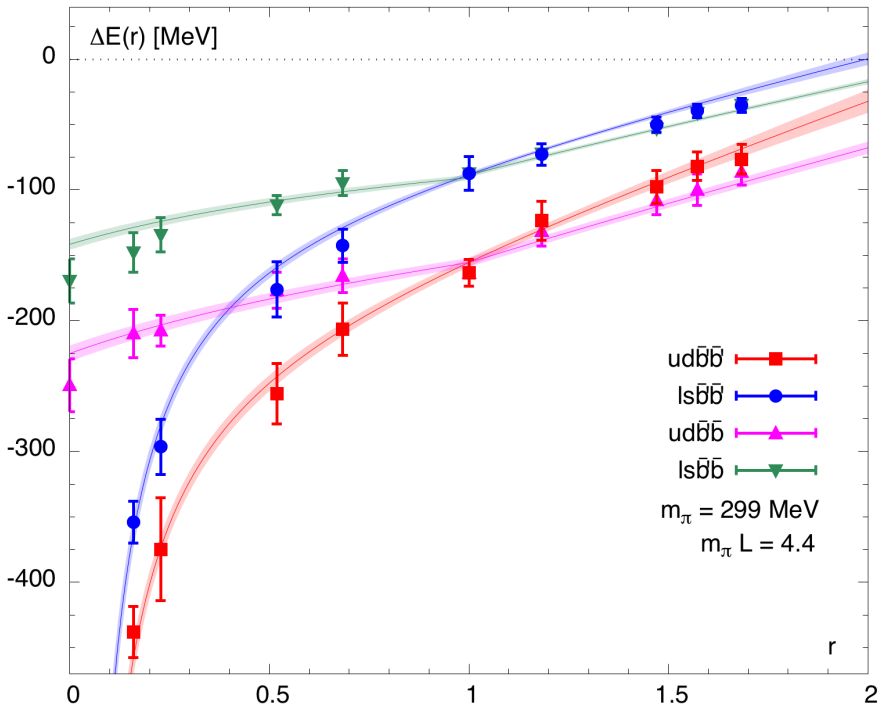
- ★ Coulomb gauge-fixed wall sources
- ★ Light quarks down to physical masses
  - ▶ Wilson-clover action
  - ▶ A larger volume to control finite volume effects
    - ○ Others in progress
- ★ Strange quarks give physical m_K at physical m_π
  - ▶ Wilson-clover action
- ★ Charm uses "Tsukuba" interpretation of relativistic heavy quark action
  - ▶ Parameters set as in Namekawa *et al.* [1104.4600]
- ★ Bottom uses NRQCD
  - ▶ Hamiltonian to $\mathcal{O}(v^4)$
  - ▶ Tree-level value of Wilson coefficients
  - ▶ Variable $m_{b'}/m_b$: $0.6 \to 6.3$

Variable heavy mass study

Francis *et al.* [1607.05214]

- ★ $ud\bar{b}\bar{b}$ clearly bound
- ★ Multiple lattice groups also find evidence of binding



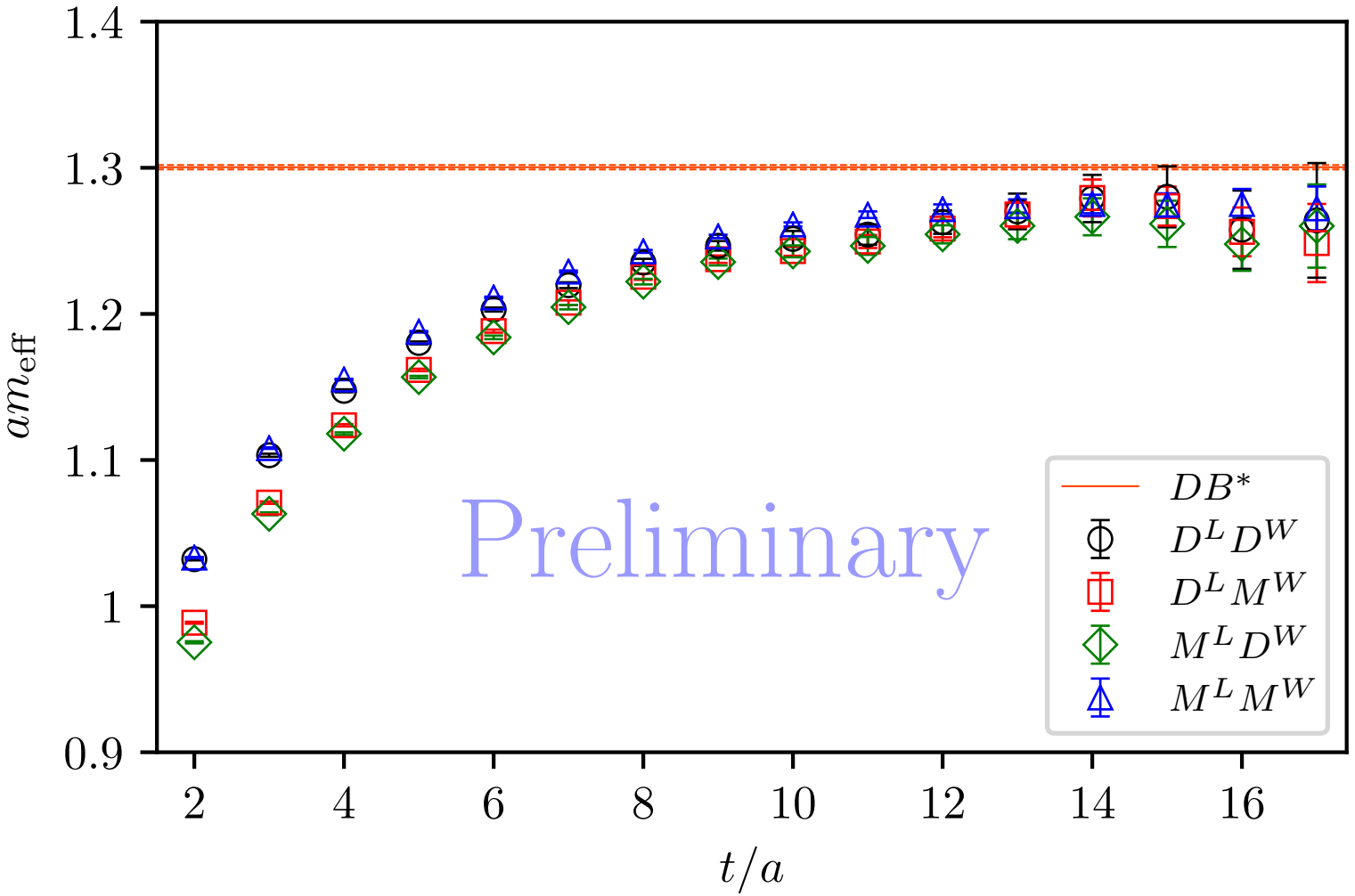


- ★ Binding increases with increasing heavy quark mass

Francis *et al.* [1810.10550]

$ud\bar{c}\bar{b}$ 1^+ state

Francis, Hudpsith, Lewis, Maltman [1810.10550]



$ud\bar{c}\bar{b}$ 1^+ state: 4×4 GEVP

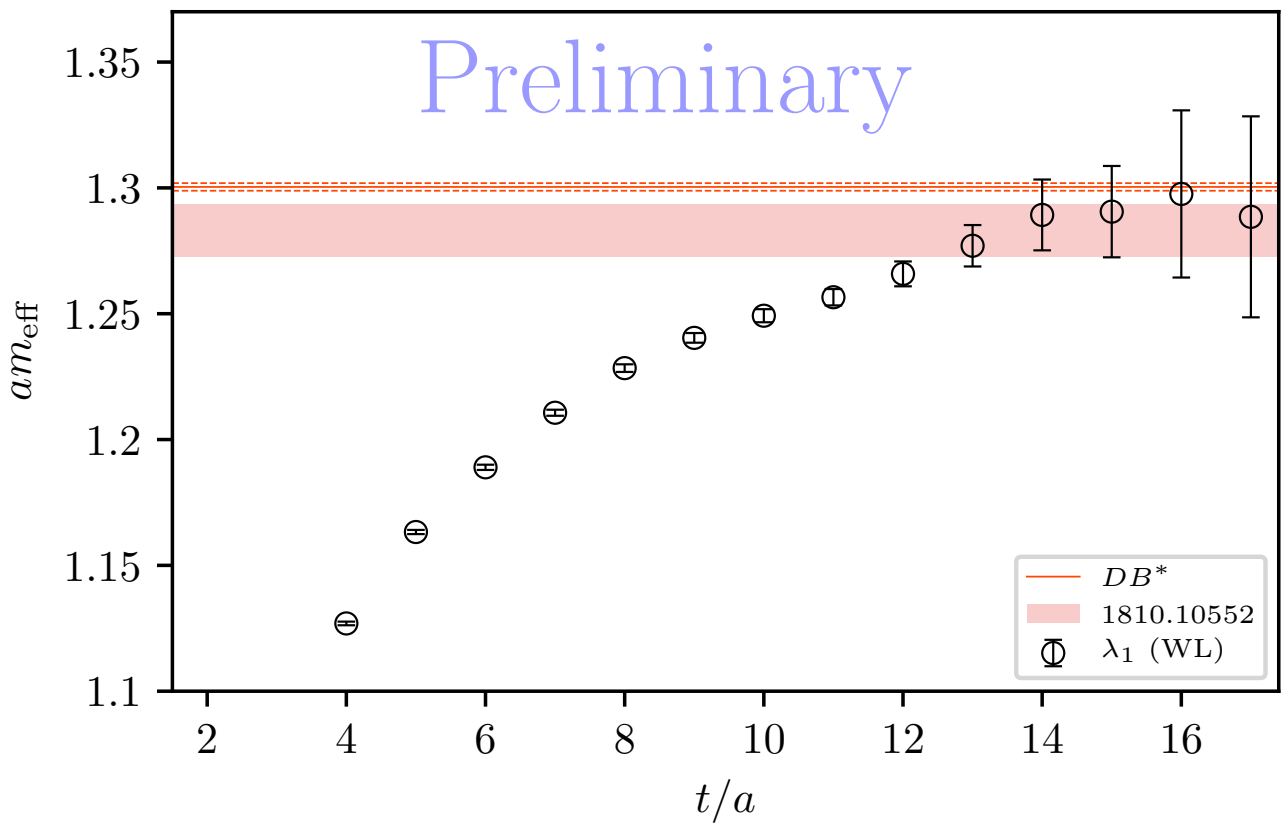
- ★ Improvements:
  - Increased operator basis
  - Wall-box set-up
  - Larger volume

$$D_{P,V_i} = (u_b^T C\gamma_5 d_c)\left[(\bar{c}_b C\gamma_i \bar{b}_c^T) - (\bar{c}_c C\gamma_i \bar{b}_b^T)\right]$$

$$D_{A_t,\sigma_{it}} = (u_b^T C\gamma_t\gamma_5 d_c)\left[(\bar{c}_b C\gamma_i\gamma_t \bar{b}_c^T) - (\bar{c}_c C\gamma_i\gamma_t \bar{b}_b^T)\right]$$

$$M_{P,V_i} = (\bar{c}_a\gamma_5 u_a)(\bar{b}_b\gamma_i d_b) - (\bar{c}_a\gamma_5 d_a)(\bar{b}_b\gamma_i u_b),$$

$$M_{I,A_i} = (\bar{c}_a I u_a)(\bar{b}_b\gamma_i\gamma_5 d_b) - (\bar{c}_a I d_a)(\bar{b}_b\gamma_i\gamma_5 u_b).$$



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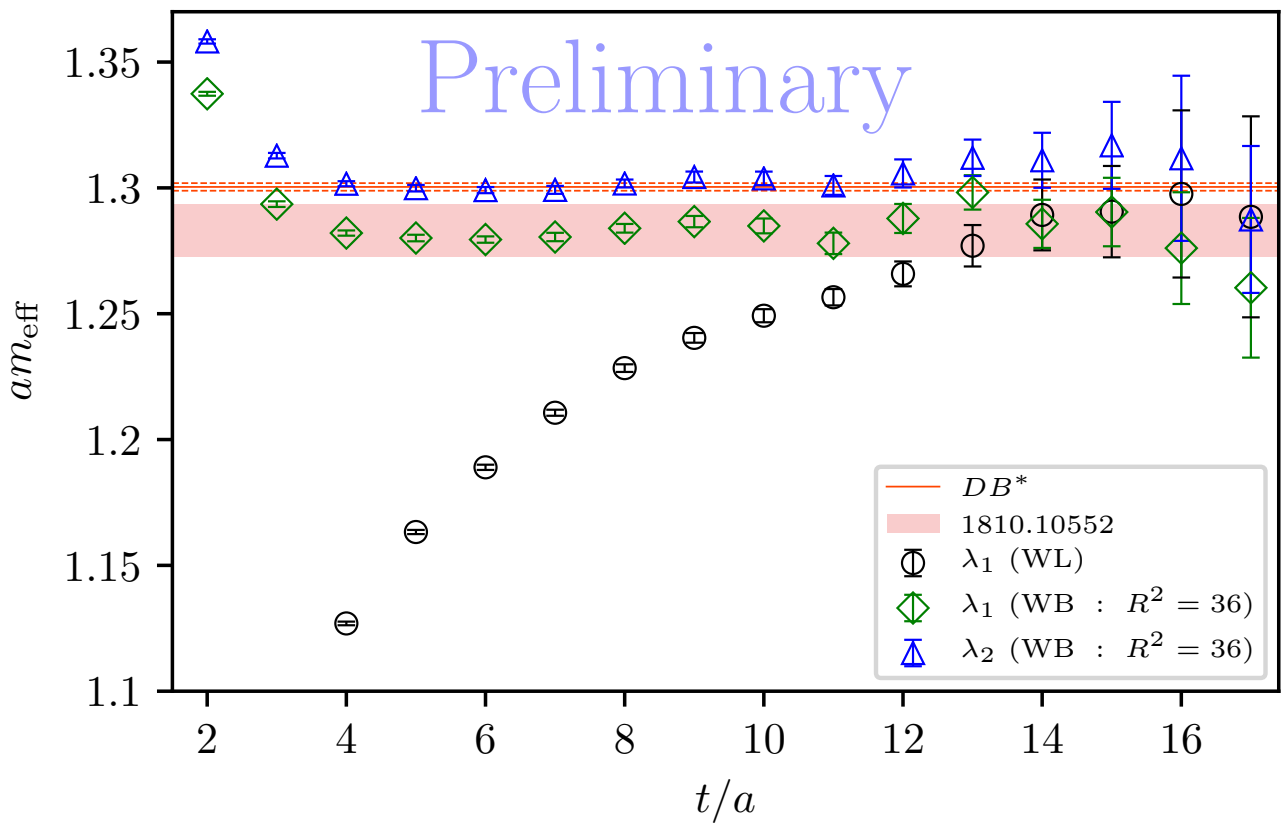
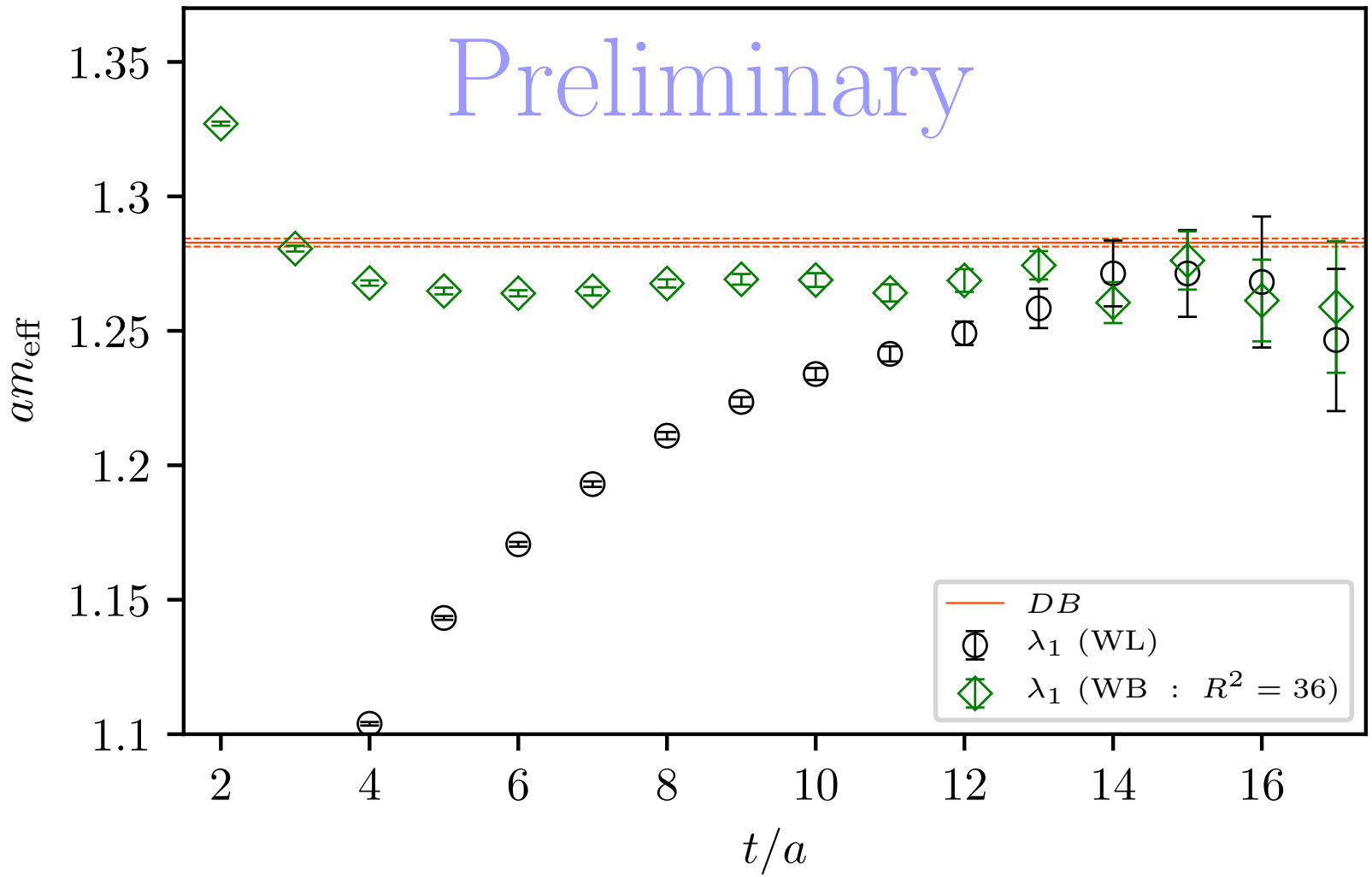


$ud\bar{c}\bar{b}$ 0^+ state: 4×4 GEVP

- ★ Analysis has begun on the 0^+ state



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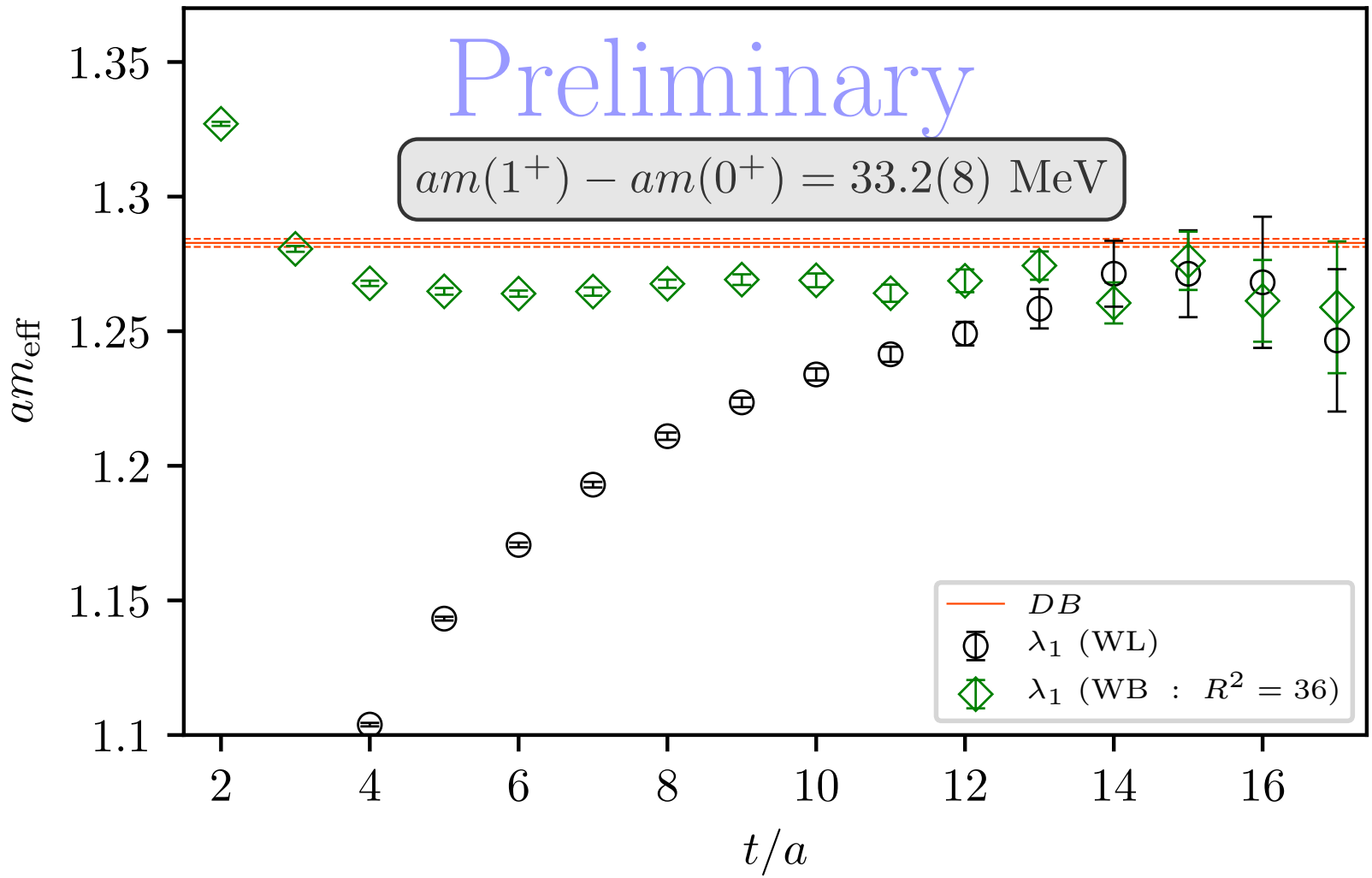
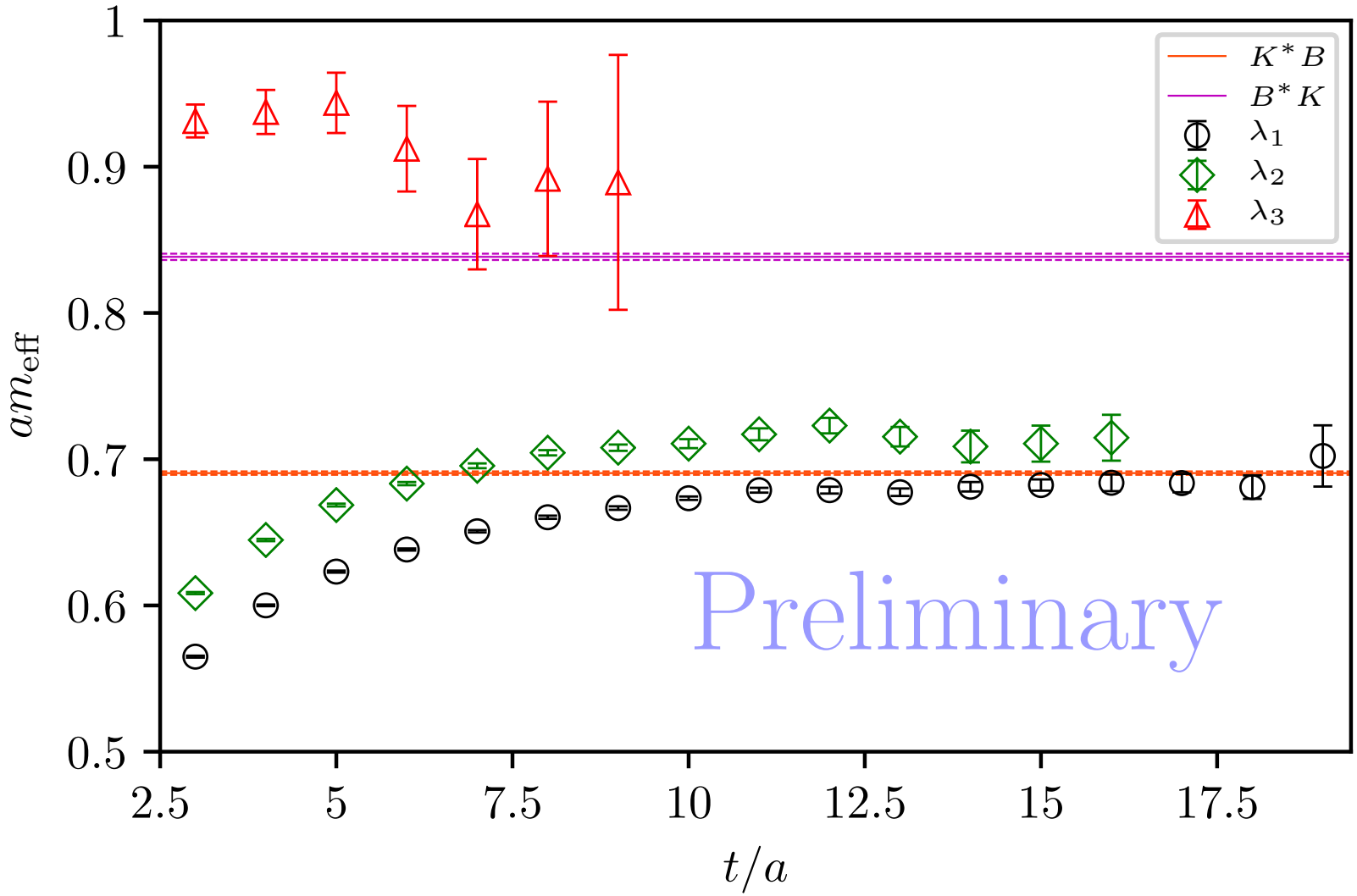


$ud\bar{s}\bar{b}$ 1^+ state 3×3 GEVP



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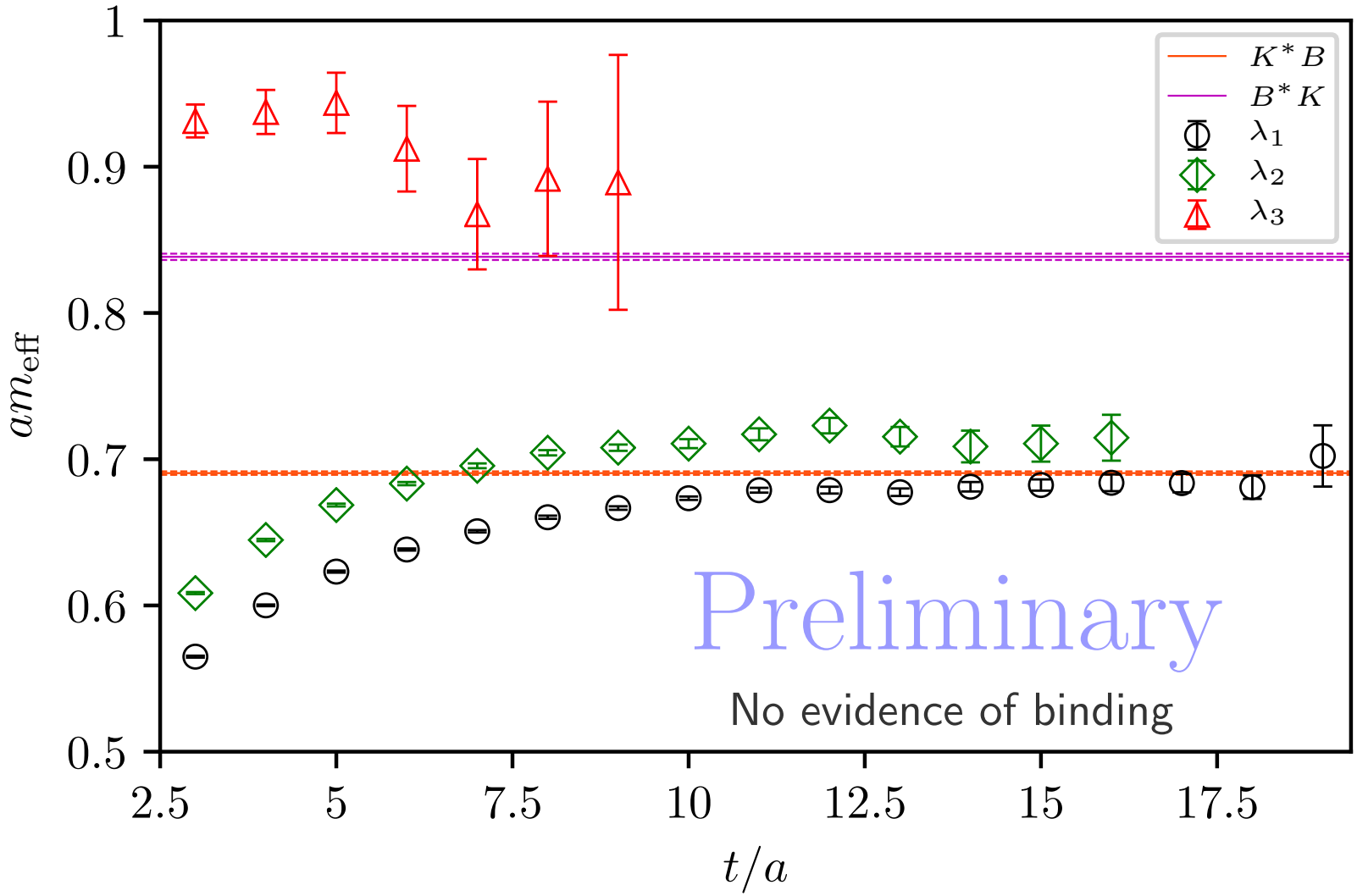

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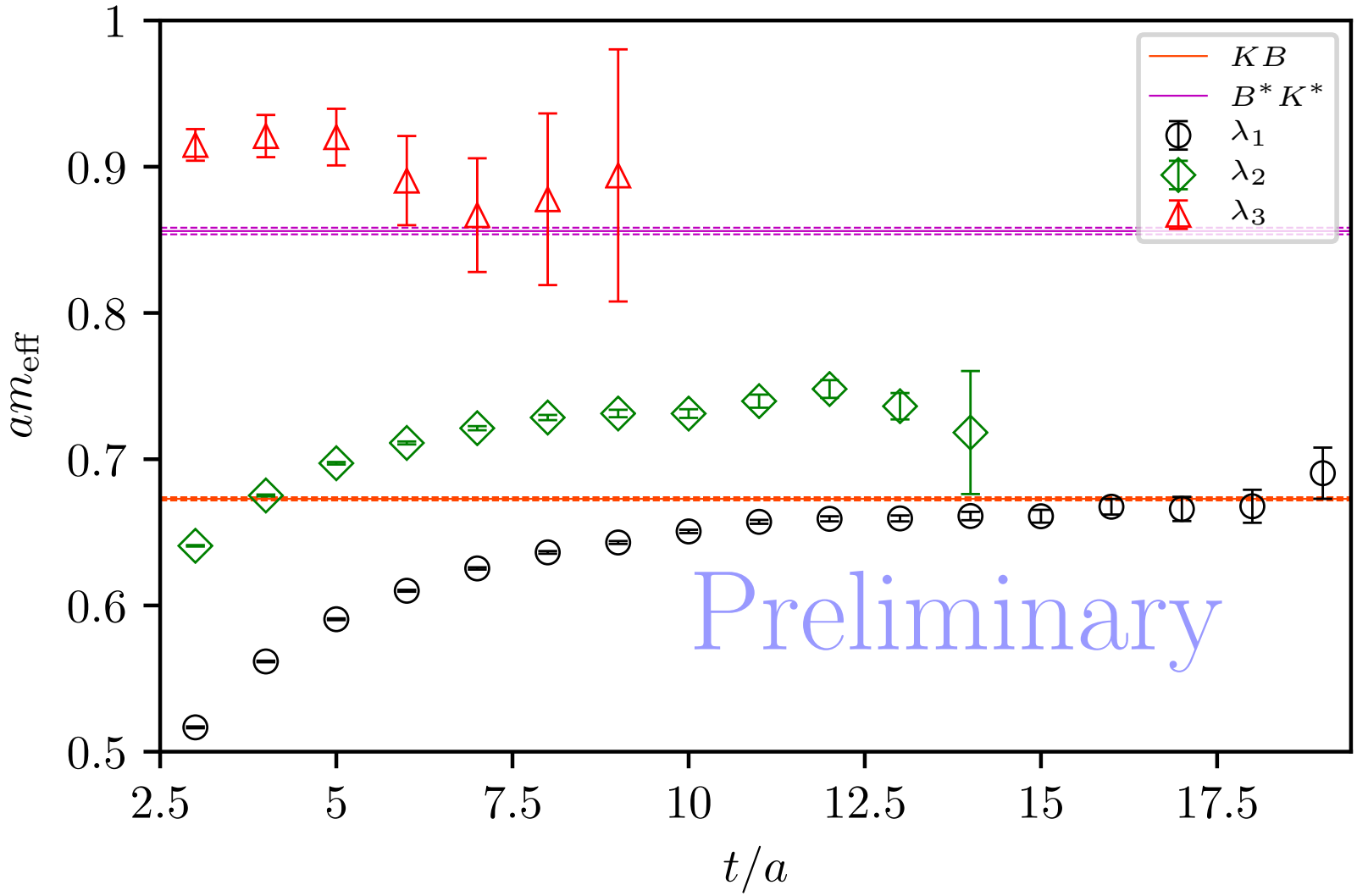

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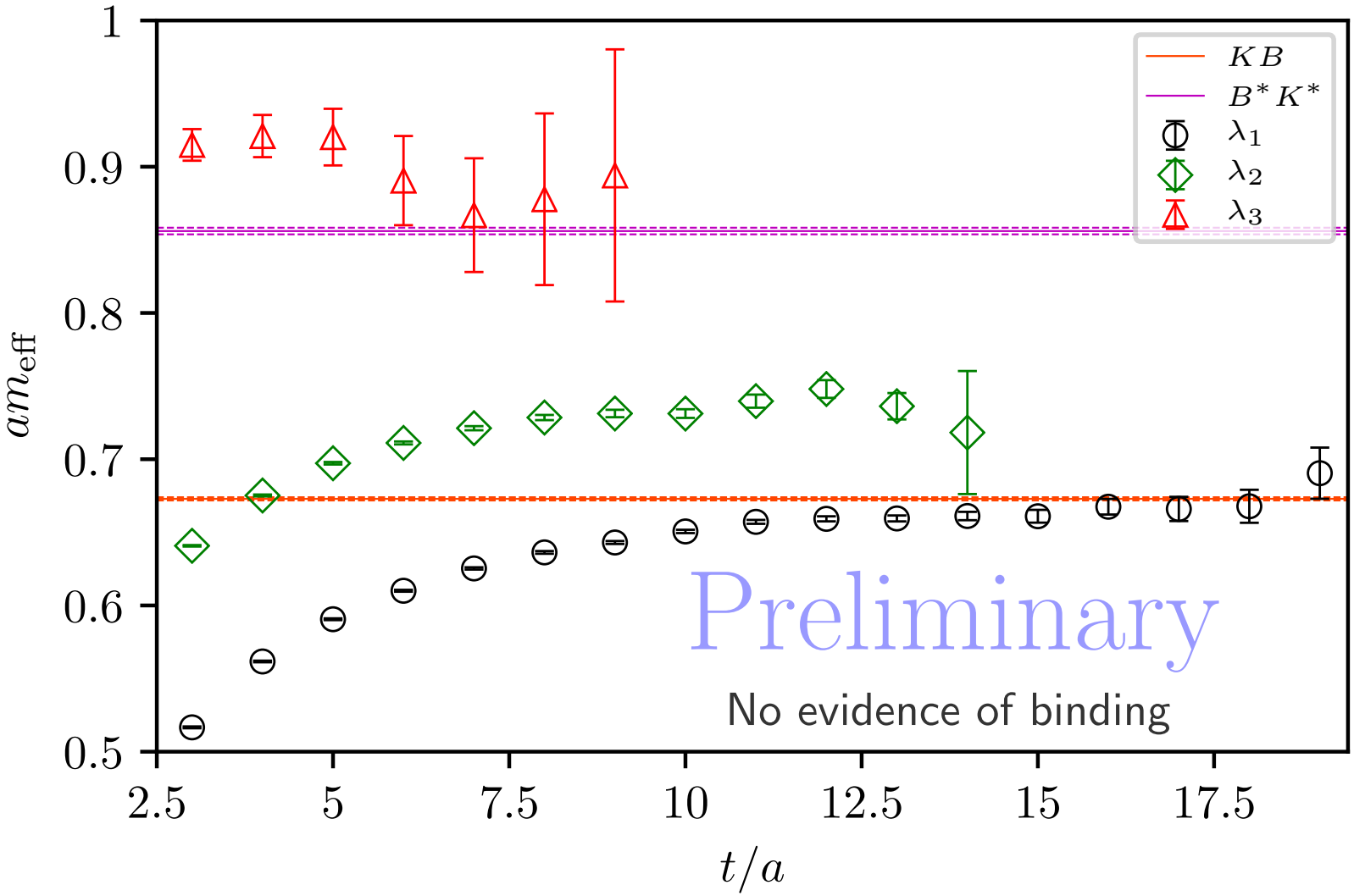
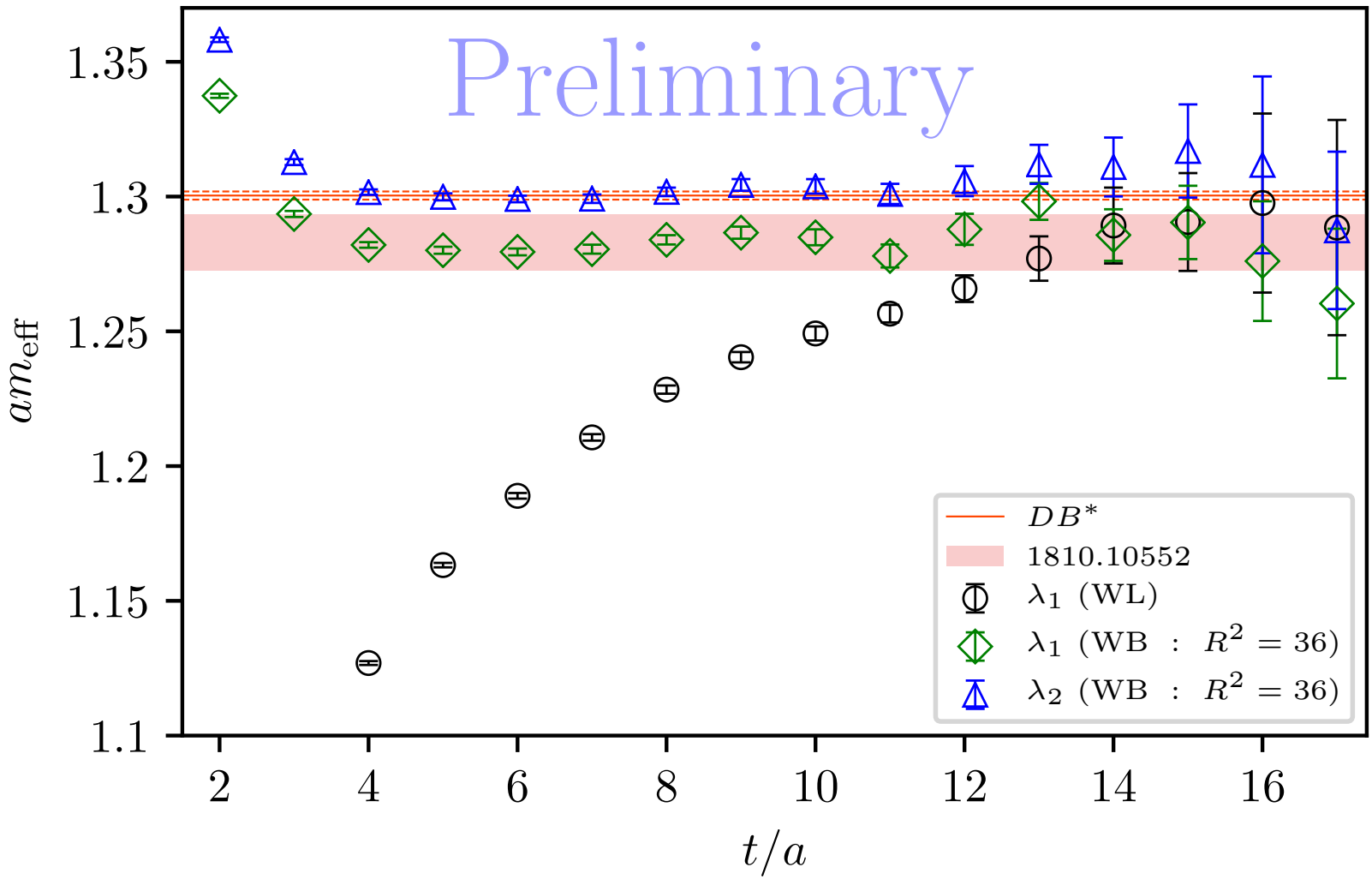
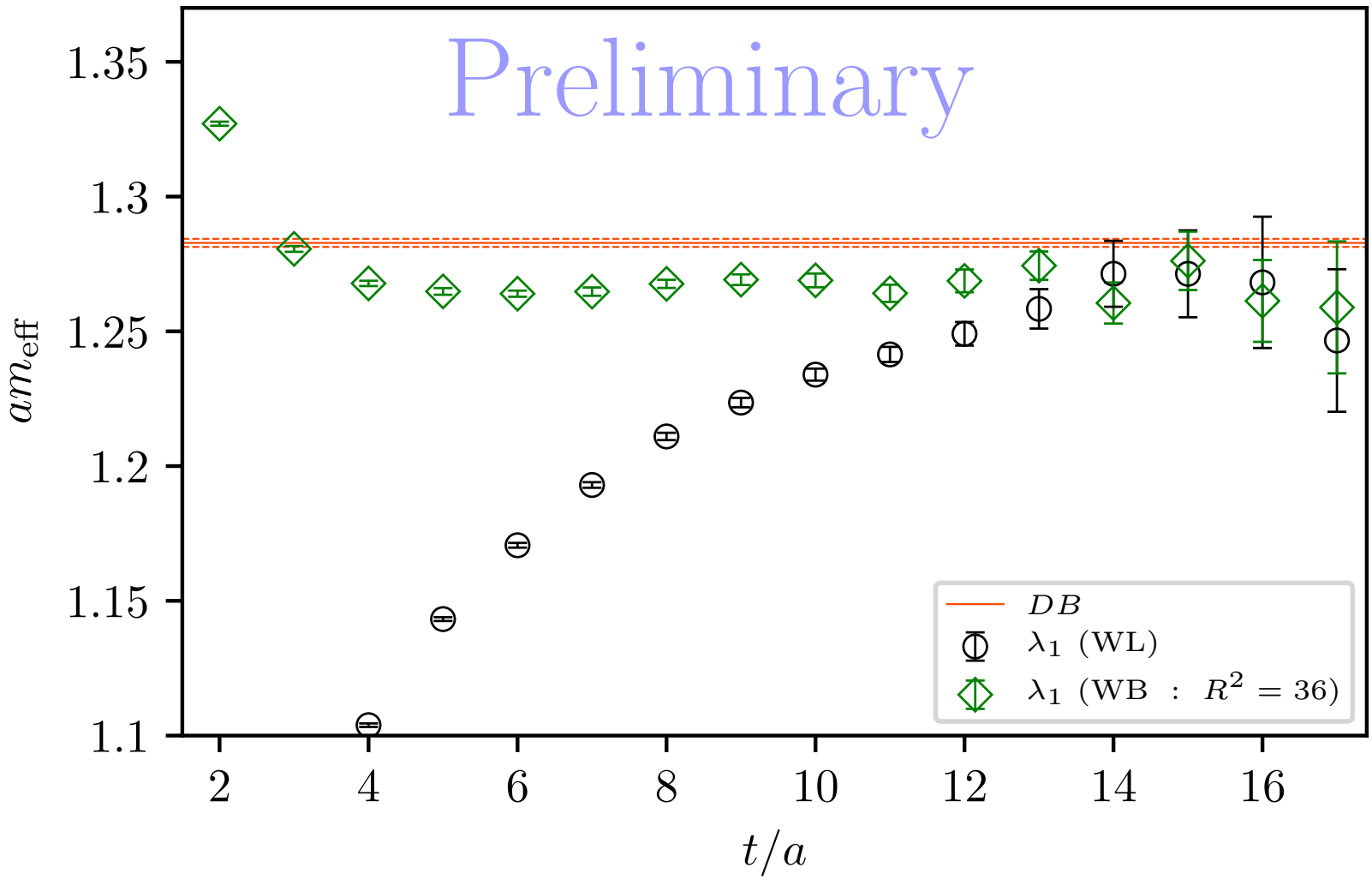


Summary

- ★ $ud\bar{b}\bar{b}$ state studied by various groups; general agreement
- ★ $ud\bar{c}\bar{b}$ 1^+ also bound; Wall-box improves plateau & solidifies this result
- ★ $ud\bar{c}\bar{b}$ 0^+ underway
  - Accurate splitting: $m(1^+) - m(0^+) = 33.2(8)\ \mathrm{MeV}$
- ★ Experimentalists should be optimistic about $ud\bar{c}\bar{b}$
- ★ Search for $ud\bar{b}\bar{b}$ will take more work, but possible
- ★ Our new result finds no evidence that $ud\bar{s}\bar{b}$ state is bound

Extras

$ud\bar{c}\bar{b}$ 1^+ alone



$ud\bar{c}\bar{b}$ 0^+ alone